

Accreting Neutron Stars & Dense Matter Physics

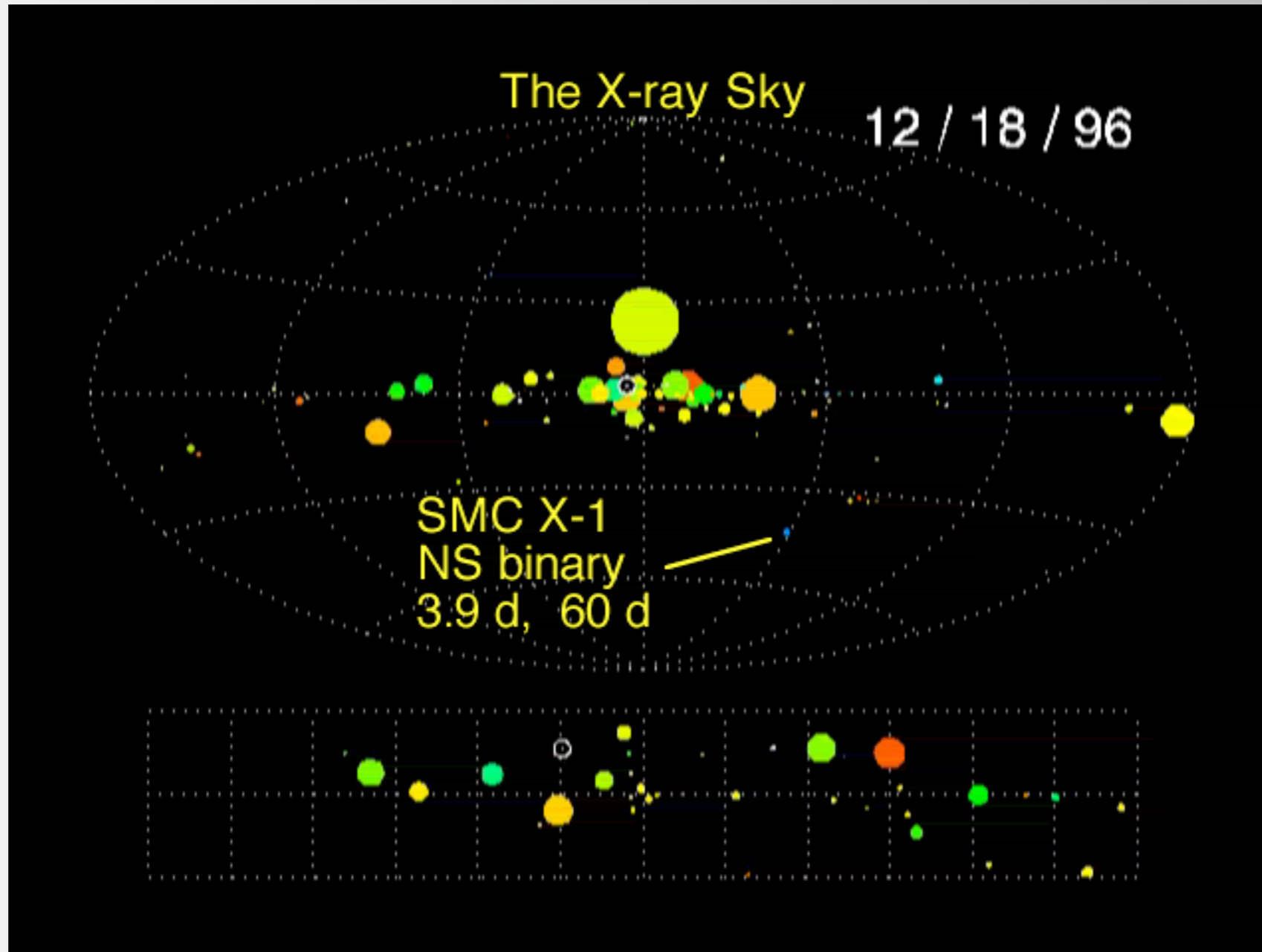
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Why accreting neutron stars?



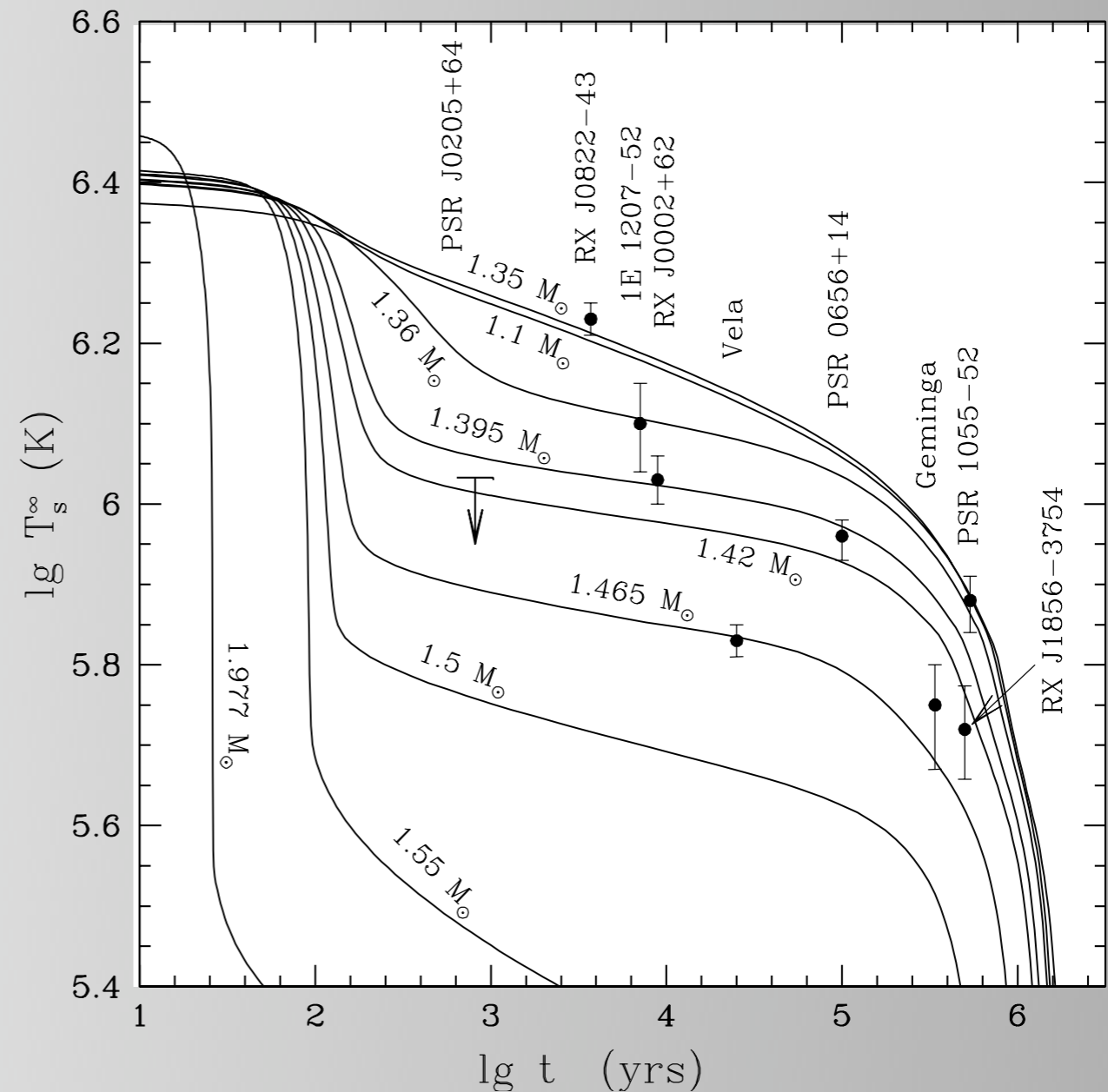
Excerpt from *The X-ray Sky Feb. 96–Nov. 99*
Movie credits: ASM teams at MIT and GSFC (<http://xte.mit.edu>)

In this talk, I'll address...

- What we can learn from accreting neutron stars
- The fate of accreted matter, and deep nuclear heating (also see talk by H. Schatz, next)
- Probing the internal structure of accreting neutron stars
 - Soft X-ray transients (with Bob Rutledge, Lars Bildsten, Slava Zavlin, & George Pavlov; Michelle Ouellette)
 - Superbursts

Cooling Neutron Stars

- For $T_{\text{eff}} < 10^5\text{--}10^6$ K ν -emission dominate cooling
 - modified Urca $nn \rightarrow npe\bar{\nu}_e$
 $\rho\epsilon_\nu \sim T^8$
 - direct Urca $n \rightarrow pe\bar{\nu}_e$
 $\rho\epsilon_\nu \sim T^6$
- May need a range of ρ_c (M) to fit observations (Tsuruta et al. 2001; Kaminker et al. 2002, Yakovlev et al. 2002)
- Drawbacks
 - **Poorly** understood spectra
 - Small numbers

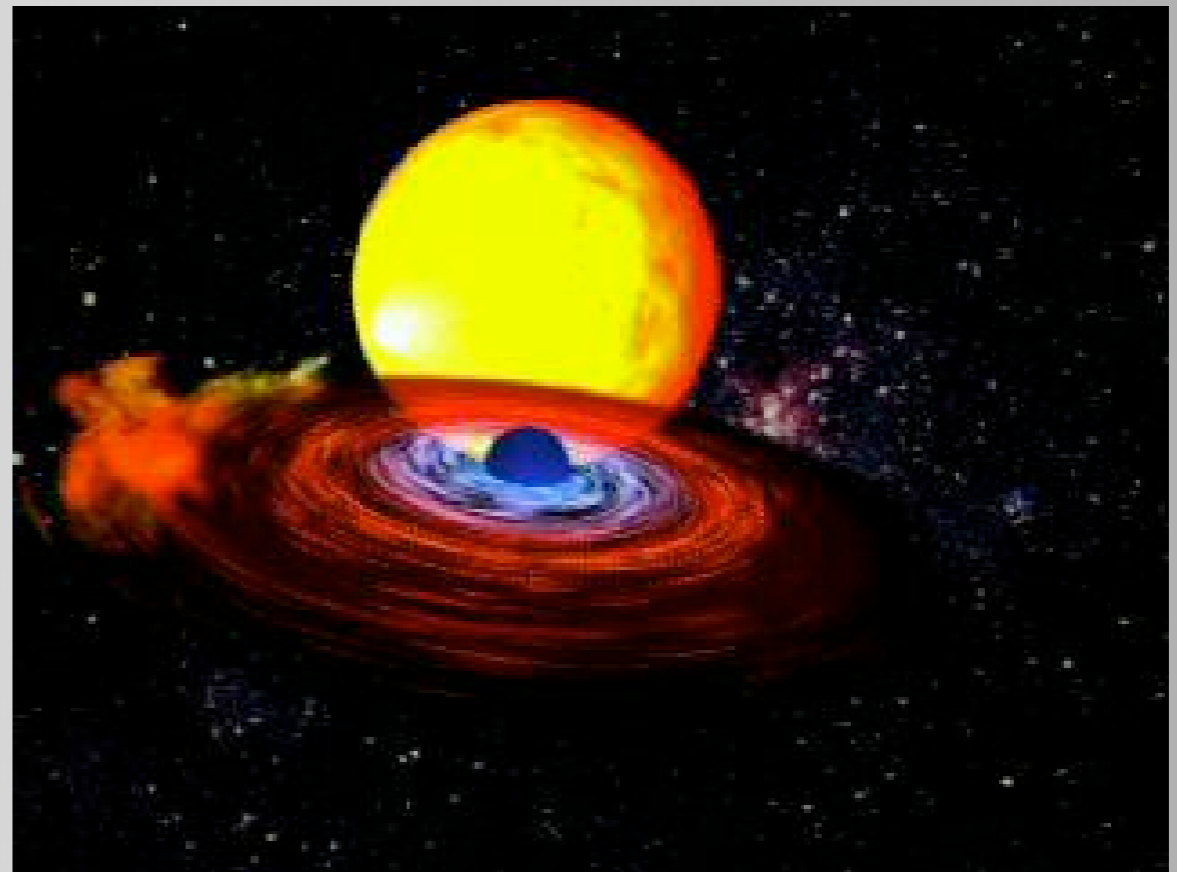


plot from Yakovlev et al. (2002)

Differences in envelope composition also important (Page et al. 2004)

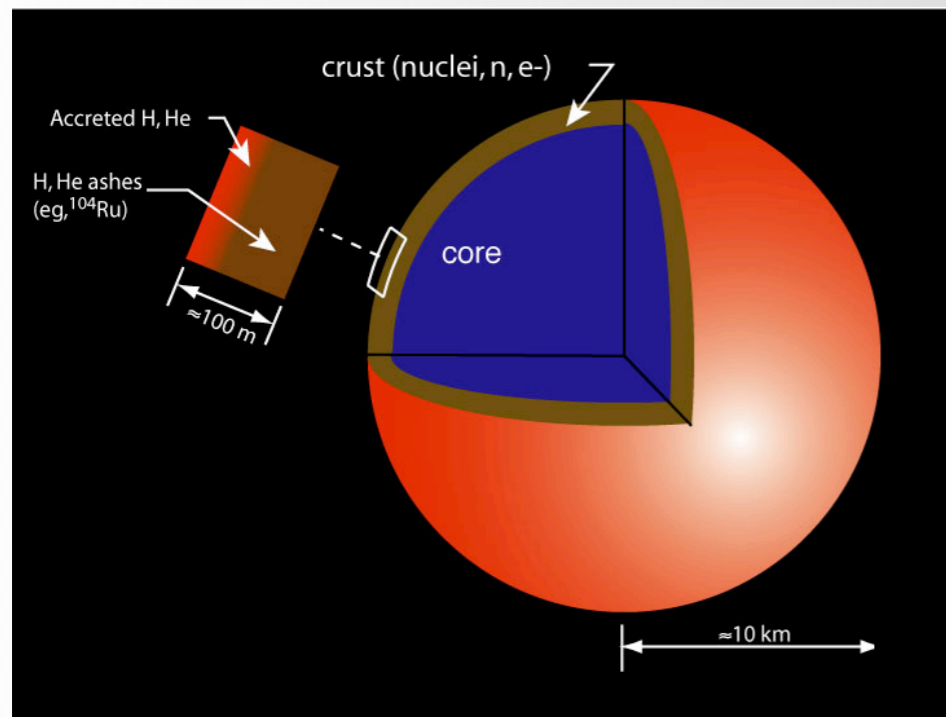
Accreting neutron stars

- ≈ 100 neutron stars are in tight binaries $P_{\text{orb}} < 1$ day with a stellar-mass companion
- Evolution of the secondary, angular momentum losses (winds, grav. rad.) cause overflow of Roche tidal radius
- H-, He-rich matter is transferred onto neutron star
- Weakly magnetized ($B < 10^{8-9}$ G)

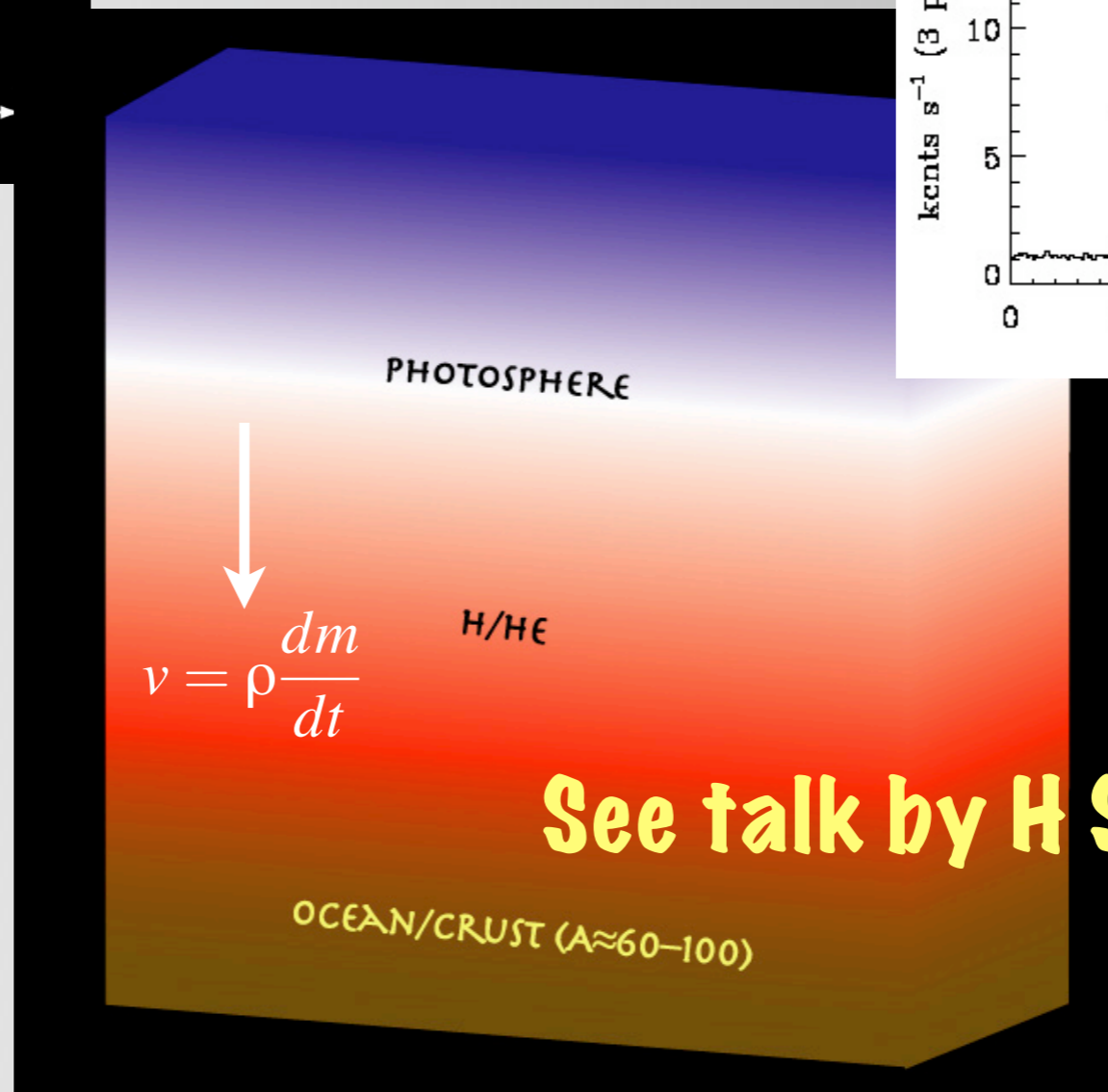
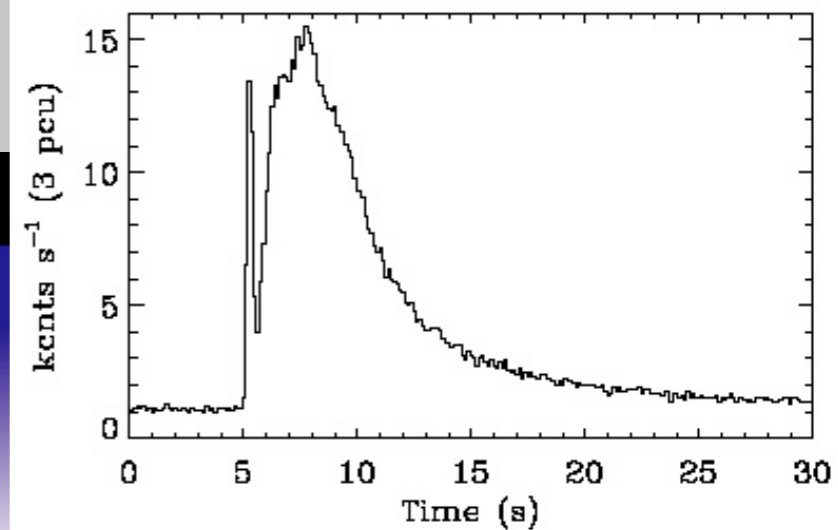


Artwork credit: NASA

Accretion replaces the crust



XRB from 1820-30, courtesy
T. Strohmayer

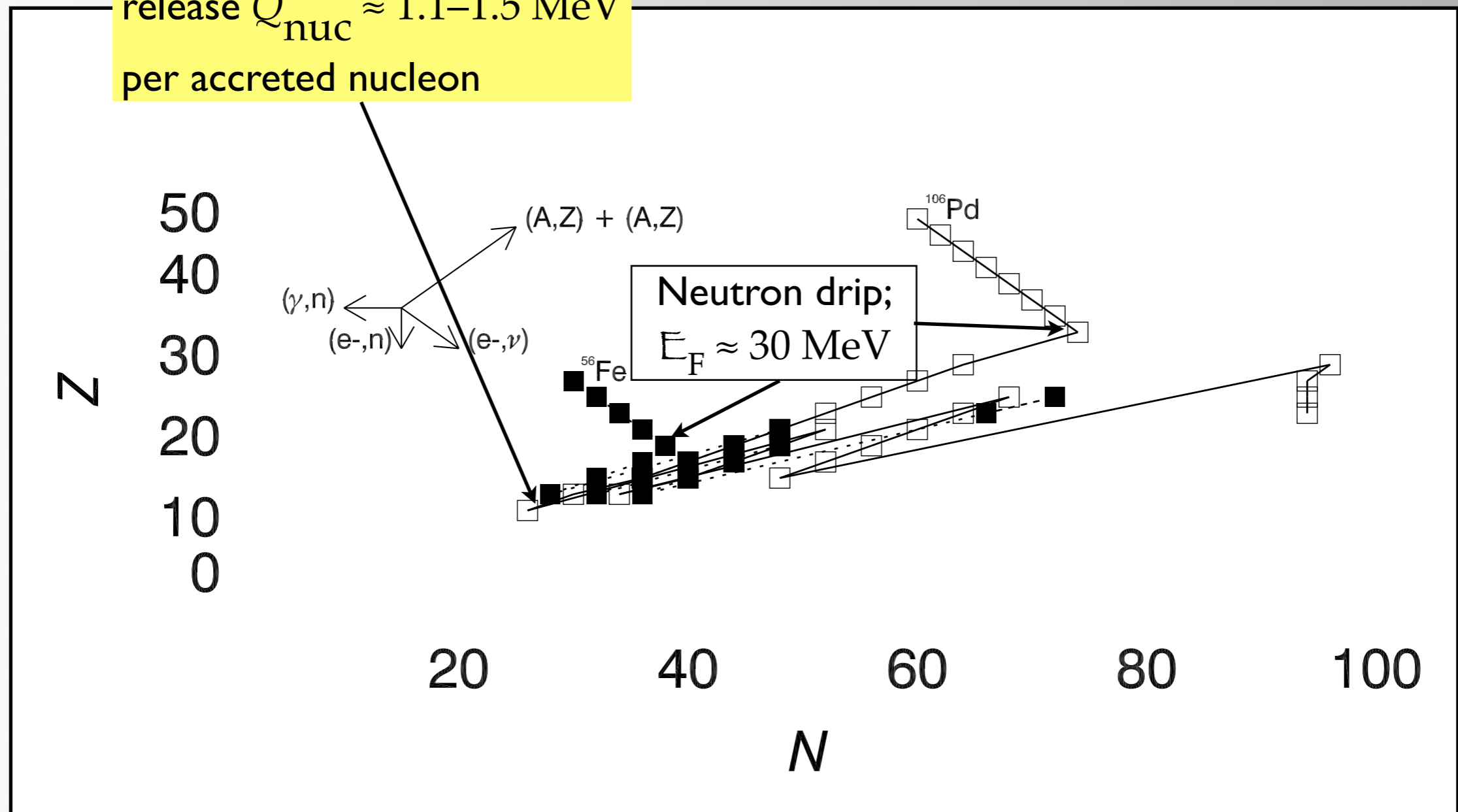


See talk by H Schatz!

Deep Nuclear Heating

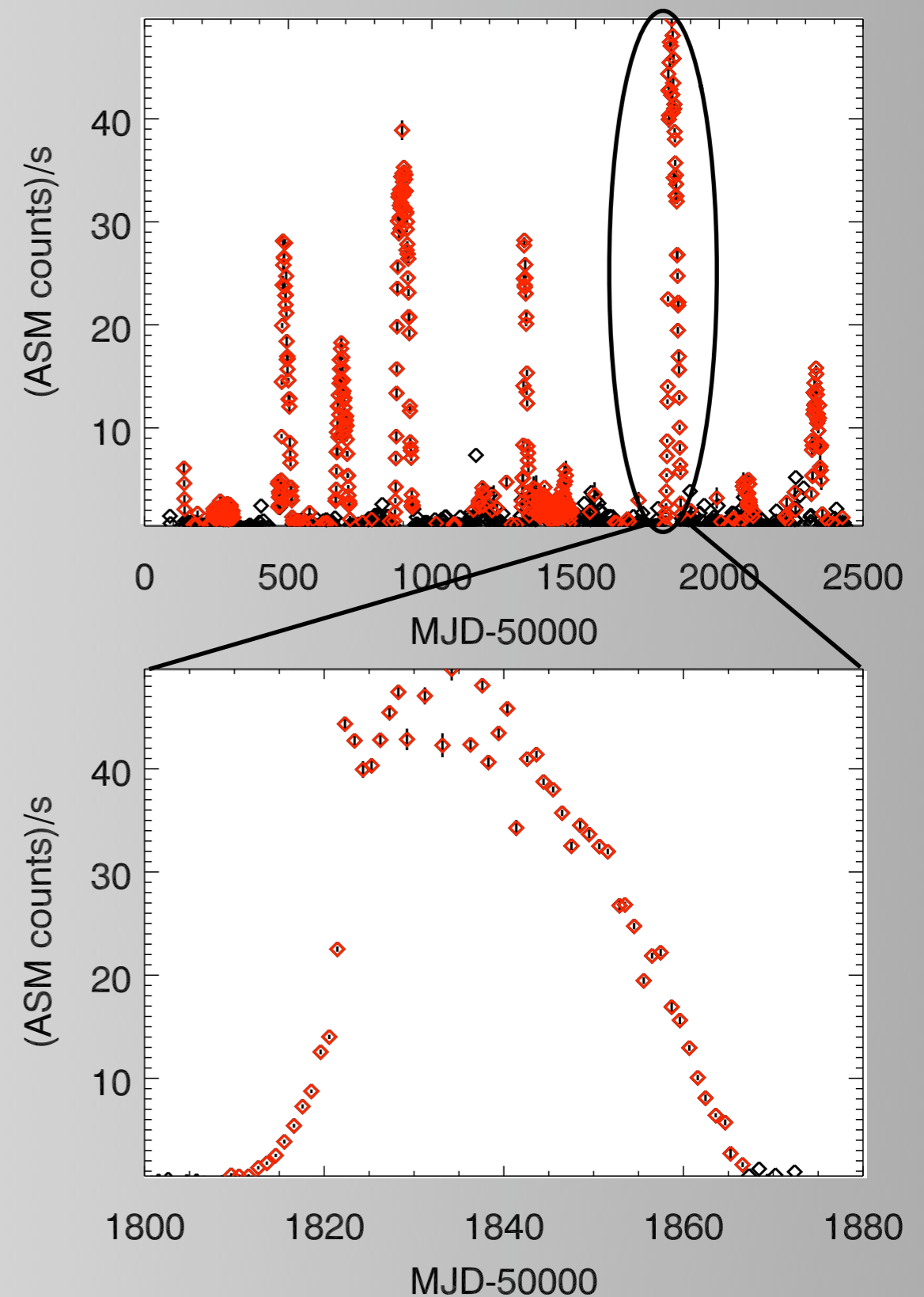
following Haensel & Zdunik 1990, 2003

Pycnonuclear reactions
release $Q_{\text{nuc}} \approx 1.1\text{--}1.5$ MeV
per accreted nucleon



Can this heating be observed?

For steady accretors, **no**
 $E_{\text{grav}} \sim 200 \text{ MeV/nucleon}$
But many sources accrete
transiently



Thermal emission from quiescent transients

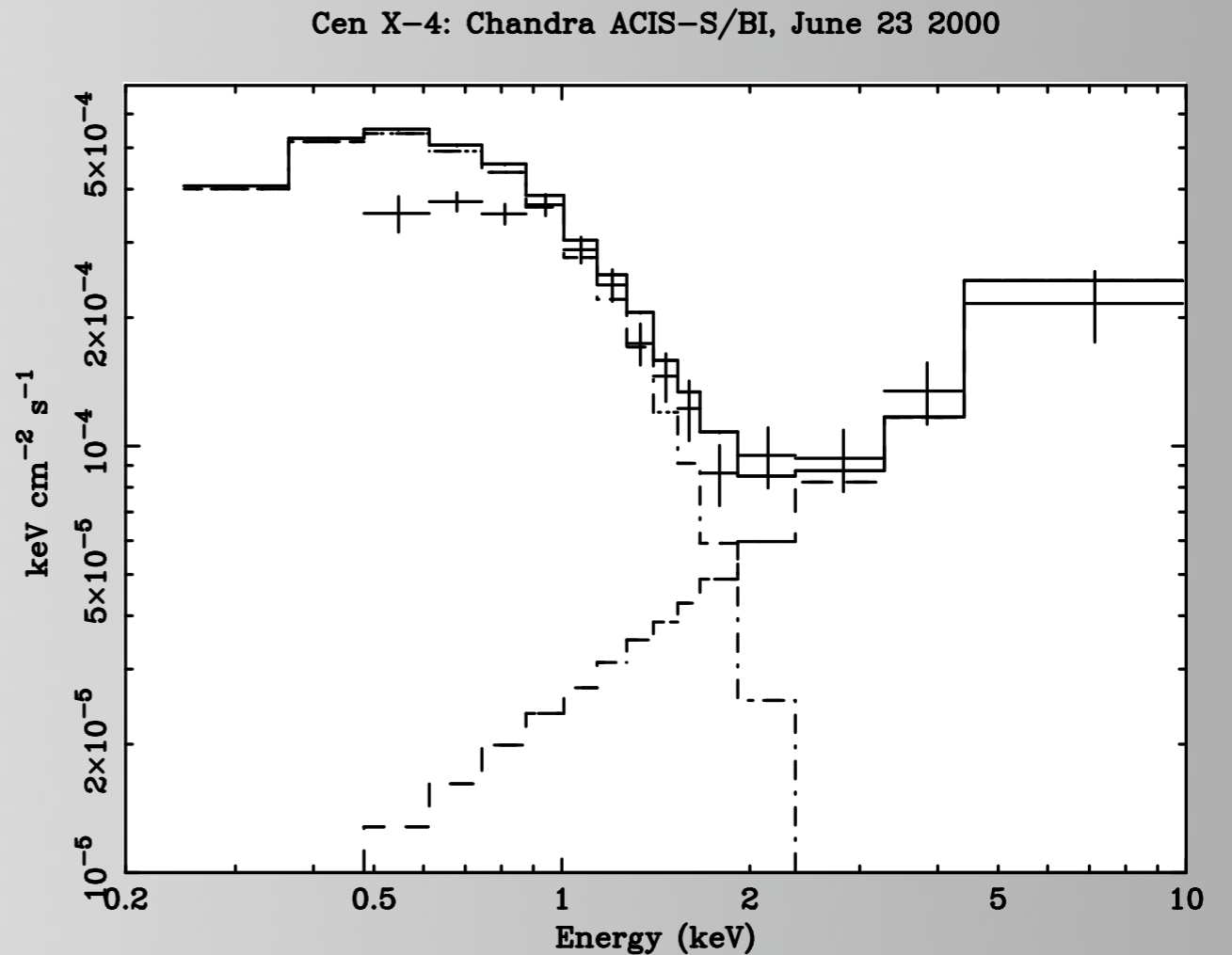
Thermal emission first detected (with *EXOSAT*) from Cen X-4 (van Paradijs et al. 1987)

$$L_q \approx 2 \times 10^{33} \text{ ergs s}^{-1}$$

Blackbody spectral fits imply

$$R_{\text{em}} < 1 \text{ km}$$

H atmosphere spectra give reasonable radii ($R_{\text{em}} \approx 10 \text{ km}$)



plot from Rutledge et al. 2001

Thermal emission: simple estimate

Brown, Bildsten, & Rutledge 1998

Crust reactions heat the core at a rate

$$L_q = Q_{\text{nuc}} \frac{\langle \dot{M} \rangle}{m_u}$$

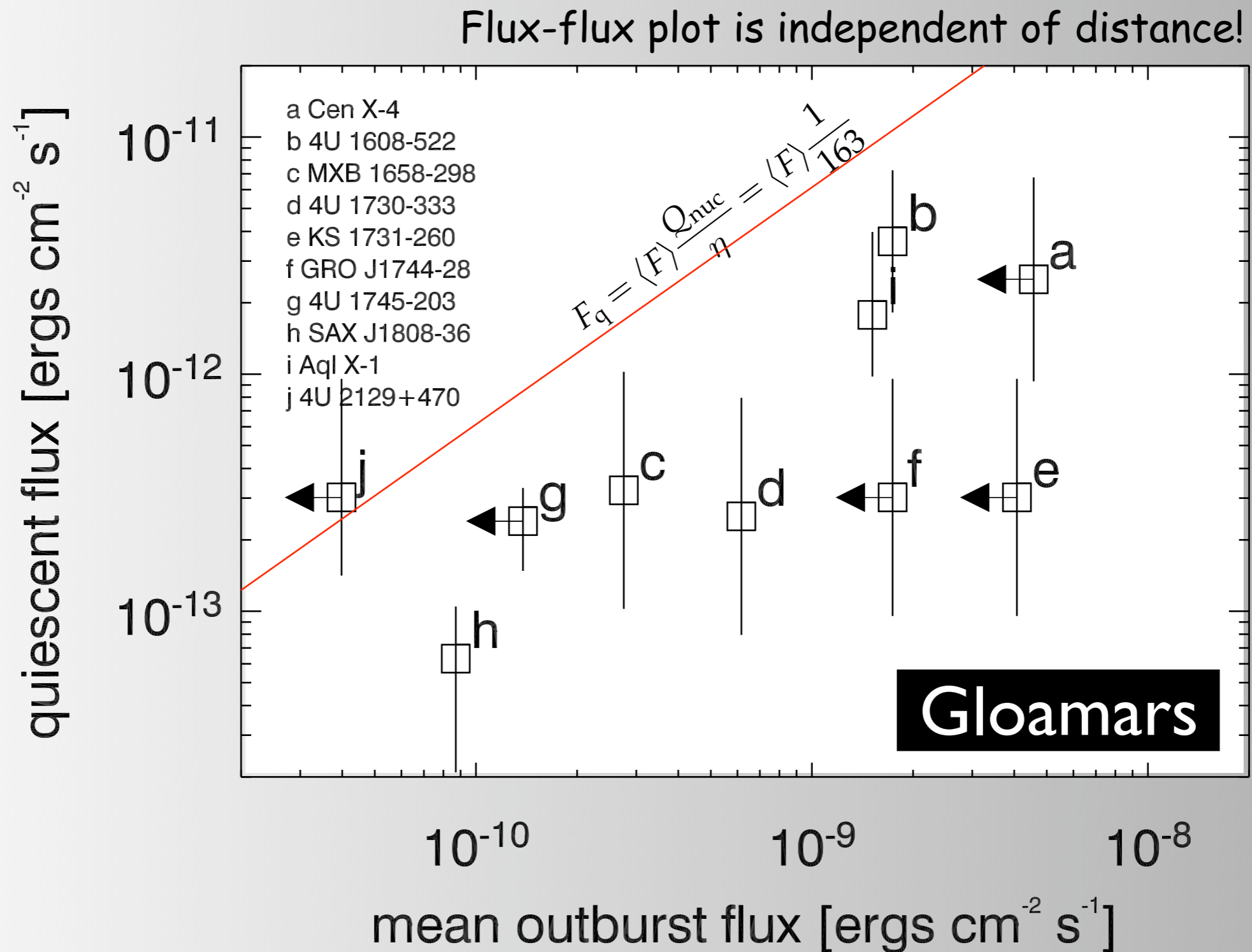
Compare Q_{nuc} with the gravitational binding energy per nucleon

$$\langle L \rangle = \eta \frac{\langle \dot{M} \rangle}{m_u} \quad \eta \approx 200 \text{ MeV}$$

In steady-state, this heat is re-radiated during quiescence, so that

$$F_q = \langle F \rangle \frac{Q_{\text{nuc}}}{\eta} \quad \leftarrow \text{No } \nu\text{-cooling!}$$

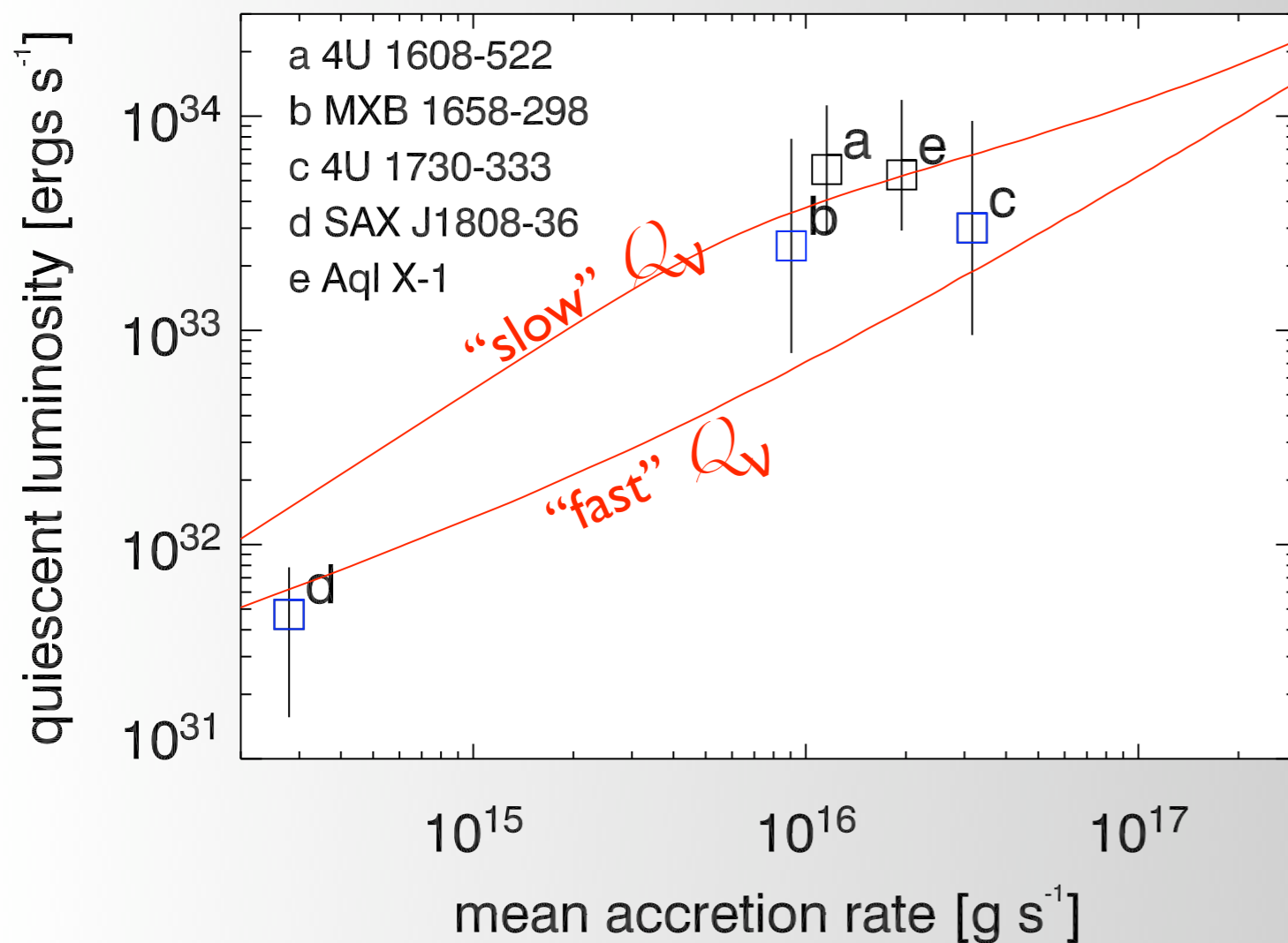
Observed neutron star transients



Brown & Rutledge, in preparation

Time-averaged flux $\langle F \rangle$ measured with *RXTE*/ASM where possible

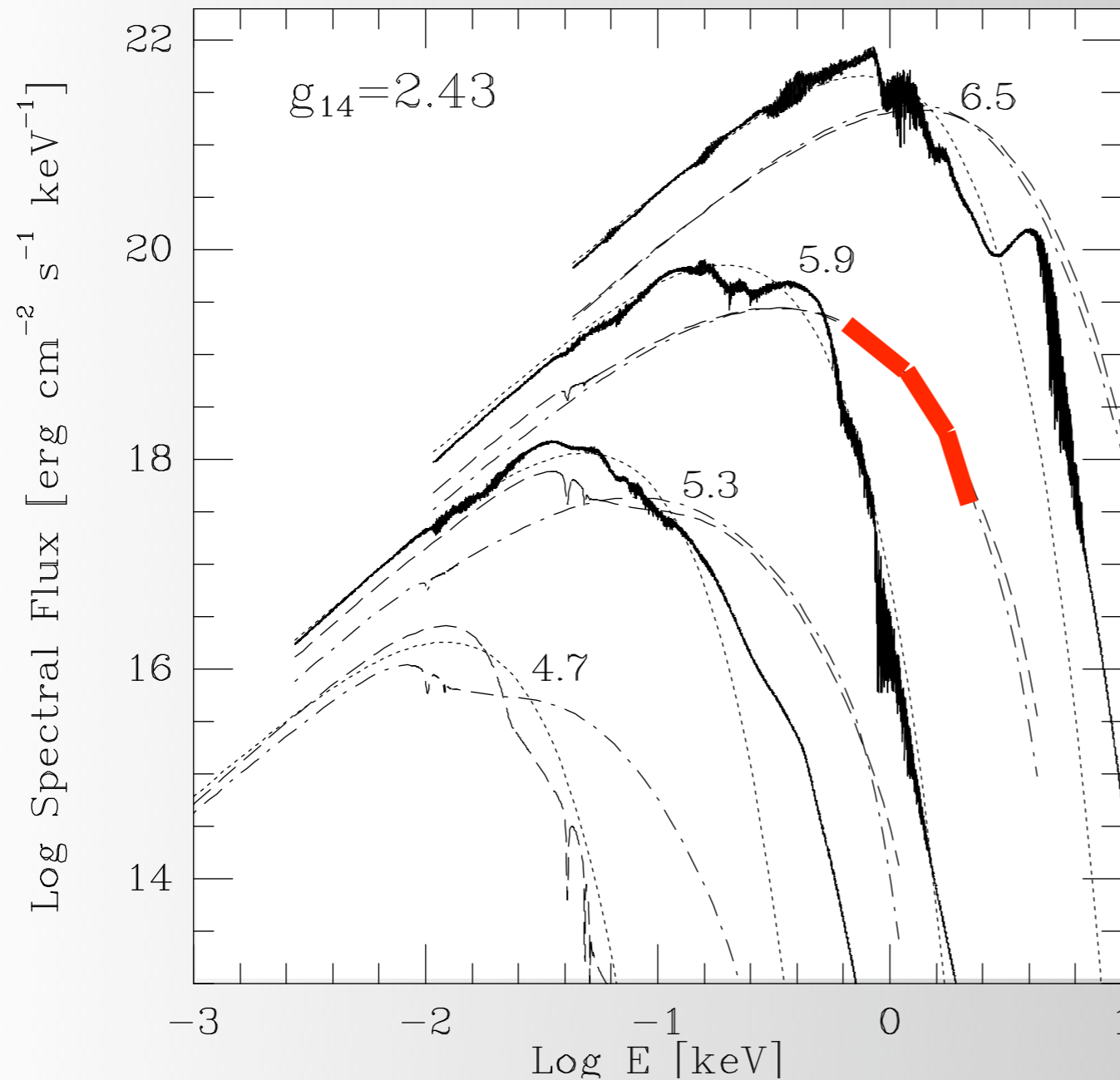
Measuring ν -cooling with neutron star transients



- Compute quiescent luminosity for different core models
 - Applicable when heating during outburst is \ll heat content of crust
 - Colpi et al. 2001; Yakovlev et al. 2003;
- *slow*: mod. urca
- *fast*: direct Urca for $r < 5$ km

Compilation of observations by Brown & Rutledge, in preparation

The one about the radius



- Unlike cooling neutron stars, spectra of accreting neutron stars are *simple*
- Weakly magnetized
- Strong gravity rapidly stratifies atmosphere: pure H, no lines
- Enhanced emission at higher E ; opacity $\propto T^{-7/2}$

Plot from Zavlin, Pavlov & Shibano (1996)

The best-measured neutron star radii

Table courtesy Bob Rutledge

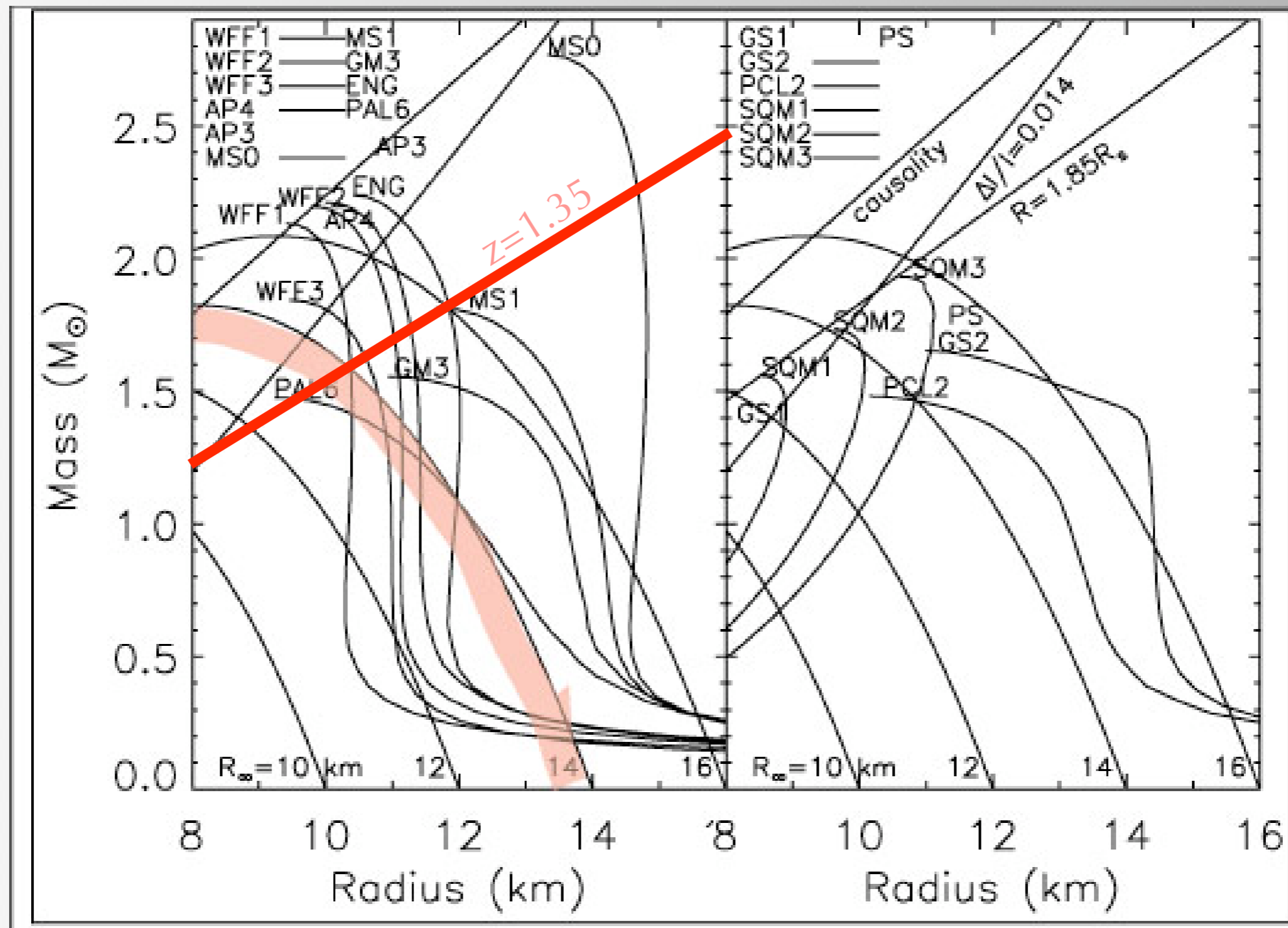
Name	R_∞ (km/D)	D (kpc)	$kT_{\text{eff},\infty}$ (eV)	N_{H} (10^{20} cm^{-2})	Ref.
omega Cen (Chandra)	13.5 ± 2.1	$5.36 \pm 6\%$	66^{+4}_{-5}	(9)	Rutledge et al (2002)
omega Cen (XMM)	13.6 ± 0.3	$5.36 \pm 6\%$	67 ± 2	9 ± 2.5	Gendre et al (2002)
M13 (XMM)	12.6 ± 0.4	$7.80 \pm 2\%$	76 ± 3	(1.1)	Gendre et al (2002)
47 Tuc X7 (Chandra)	34^{+22}_{-12}	$5.13 \pm 4\%$	84^{+13}_{-12}	$0.13^{+0.06}_{-0.04}$	Heinke et al (2003)
M28 (Chandra)	$14.5^{+6.9}_{-3.8}$	$5.5 \pm 10\%$	90^{+30}_{-10}	26 ± 4	Becker et al (2003)

Distances: Carretta et al (2000), Thompson et al (2001)

Caveats:

- All but 47 Tuc ID'd by X-ray spectrum
- 3–5% calibration uncertainties
- In omega Cen and 47 Tuc, binary counterpart was found after X-ray spectral identification.

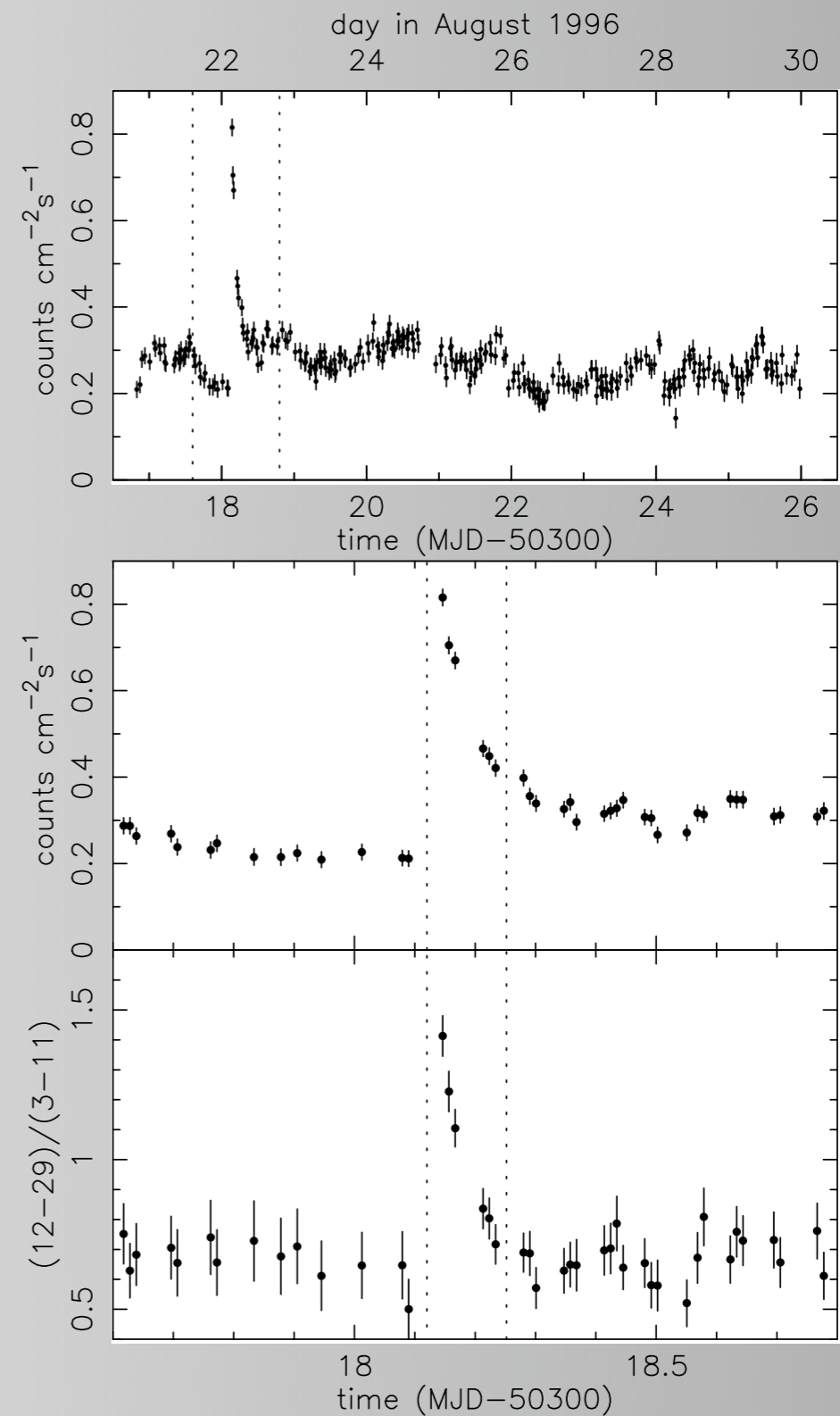
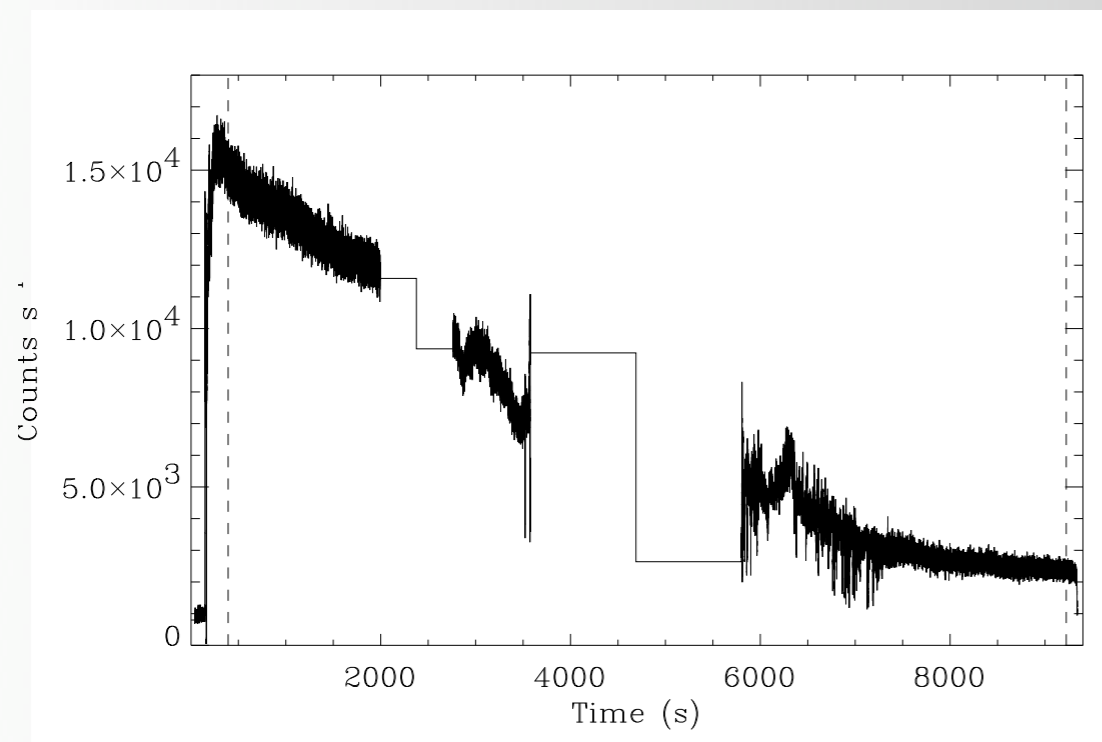
Radius constraints on eos



Lattimer & Prakash 2001

Superbursts—they are indeed super!

Burst from 4U1820–30; Strohmayer & Brown 2002



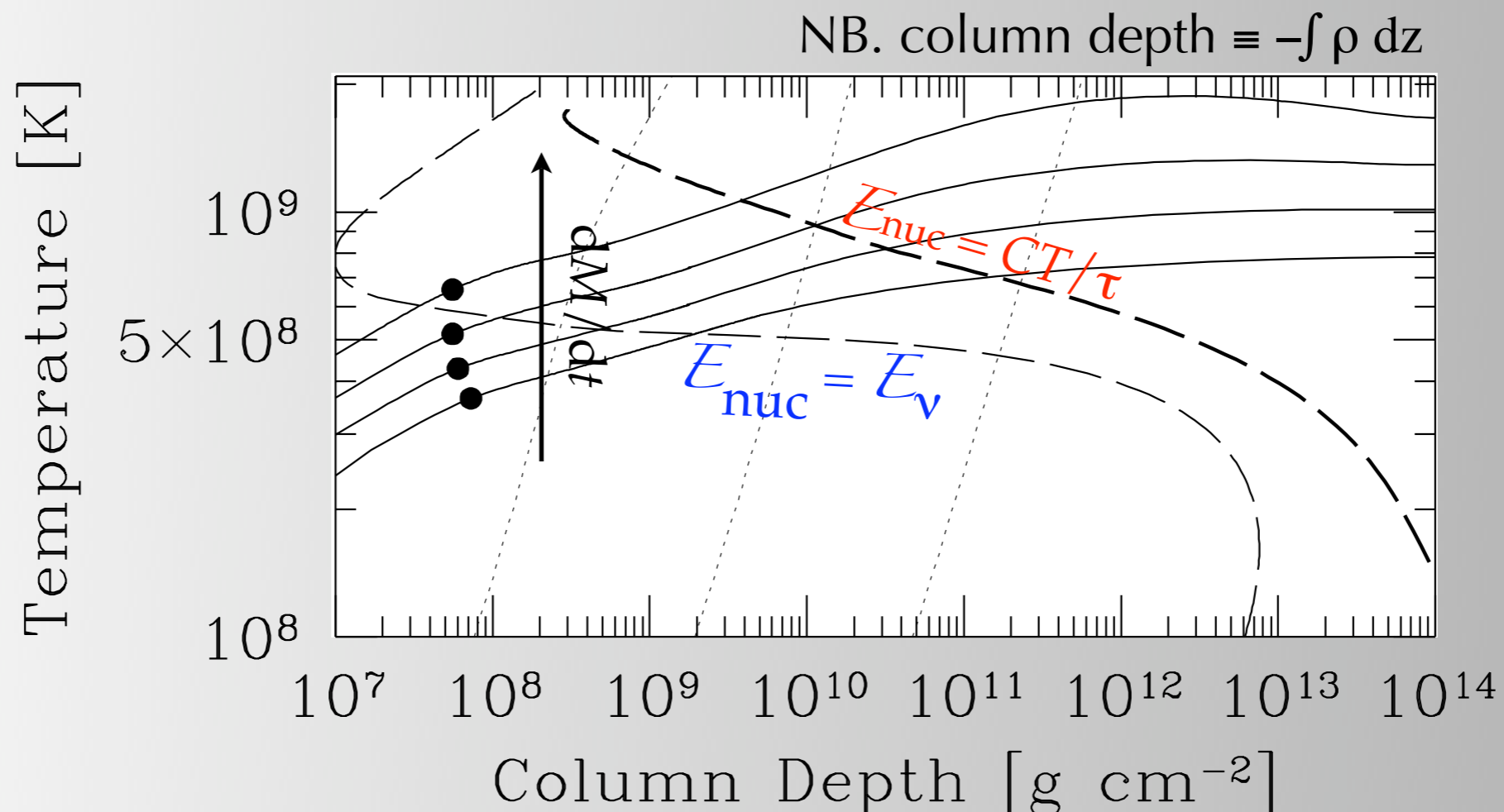
from Cornelisse et al. 2000

Superbursts

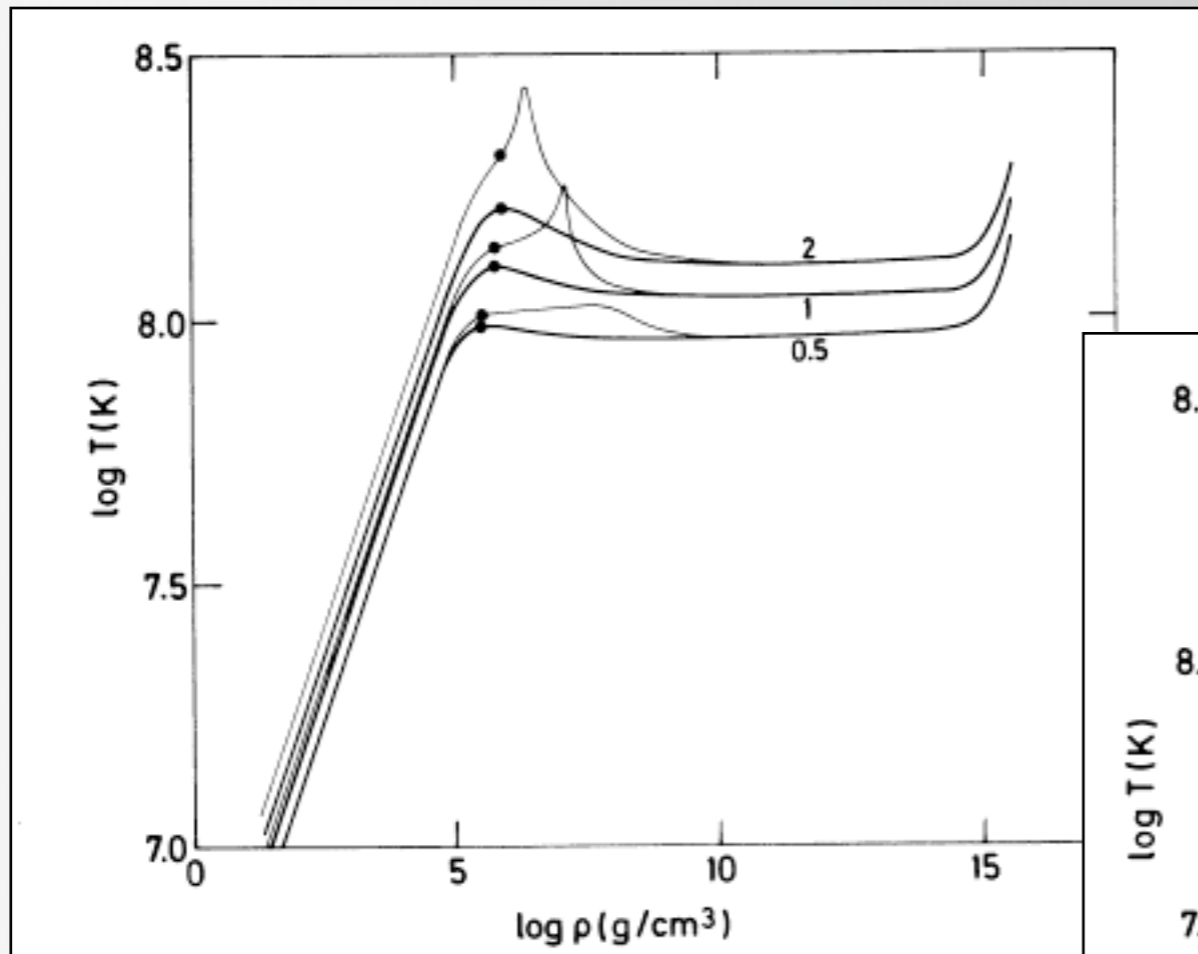
- For 4U 1636-536, 3 bursts over 4.7 years (Wijnands 2001, Kuulkers 2004)
- Mean recurrence time ~ 1.5 yr (in't Zand 2004)
- Duration: 2–12 hrs (Kuulkers et al. 2002)
- Energetics: $E < 10^{42}$ ergs
- Fuel:
 - ^{12}C ignition (Cumming & Bildsten 2001), $X=0.1$
 - photodisintegration of heavy nuclei (Schatz et al. 2003),
- Use cooling timescale (burst quenching) to get ignition column (Cumming & MacBeth 2004)

Prior estimates of recurrence times and energetics for *pure carbon* ignition

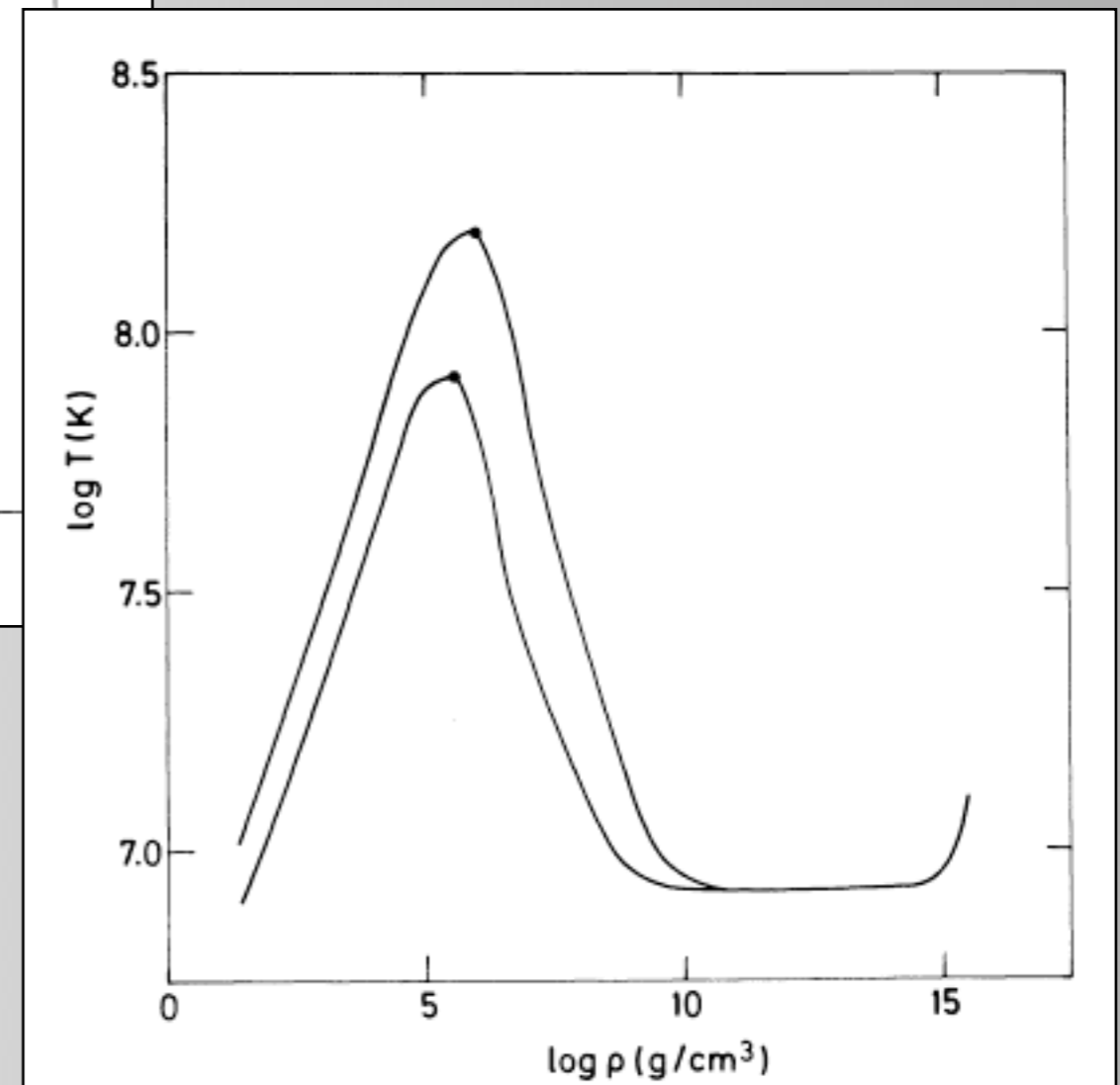
- Bursts should be either very energetic...
 - 10^{44} ergs per (10–100 yr) (Taam & Picklum 1978)
- ...or the local accretion rate should be large (eg, magnetic channeling)
 - 10^{41} ergs per (hrs–days) for very high accretion rates (Brown & Bildsten 1998)



Without deep heating...



eg, Fujimoto et al. 1987



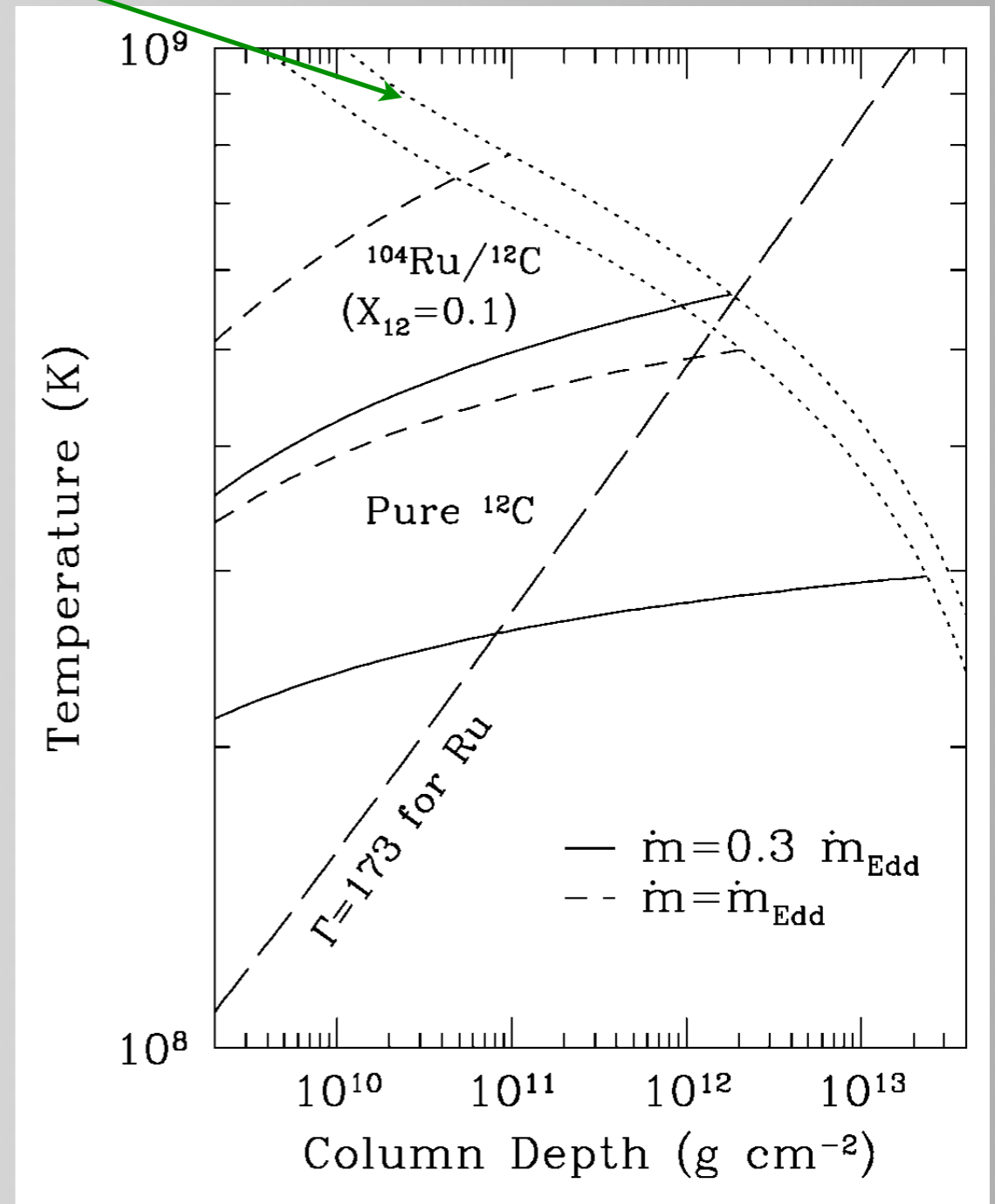
With deep heating...

Thin-shell estimate for instability
(Hansen & Van Horn 1975)

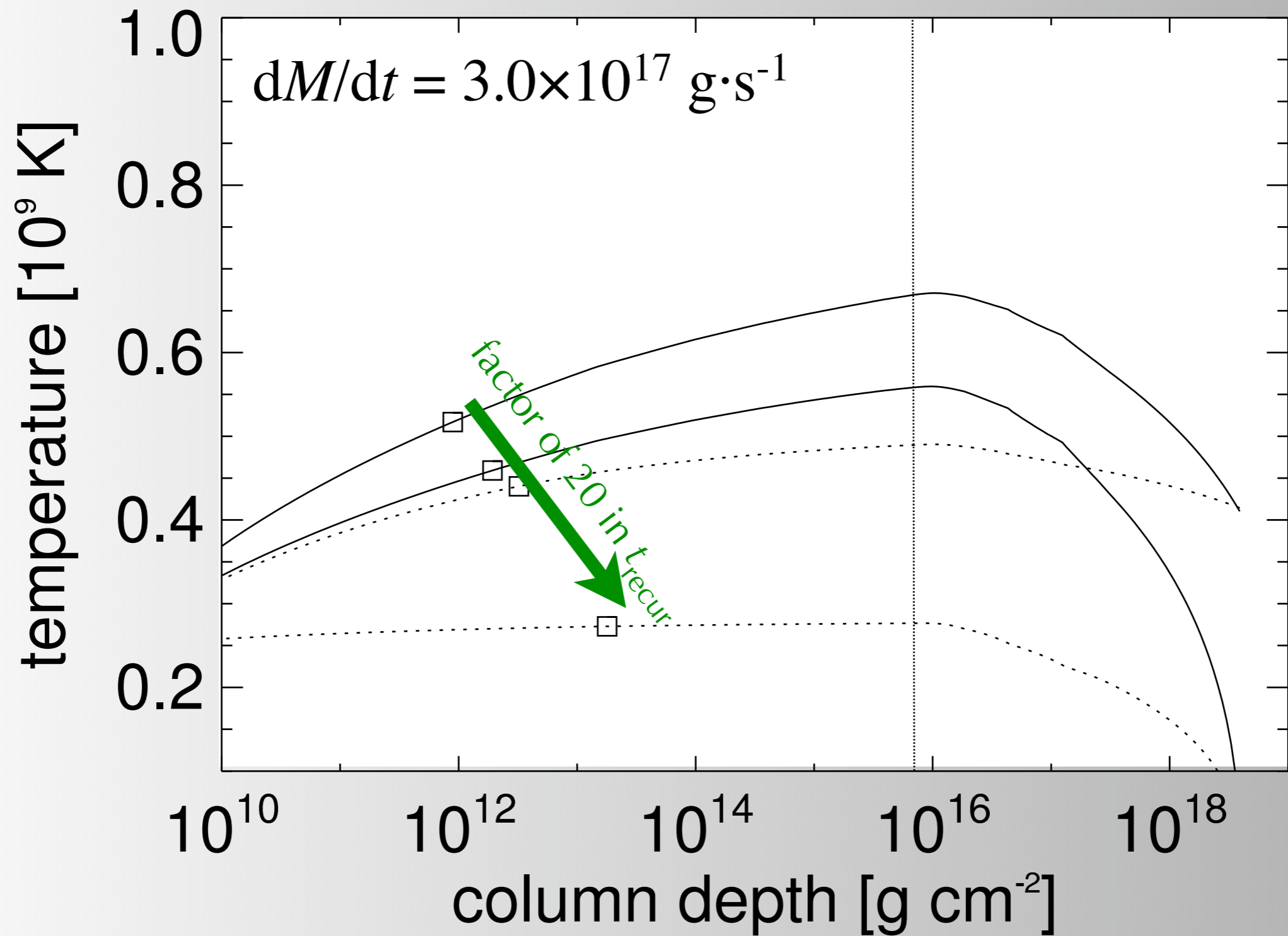
$$\partial_T \ln \epsilon_C > \partial_T \ln \eta$$

Cumming & Bildsten proposed
that thermal flux from crust
reactions would lead to earlier
ignition

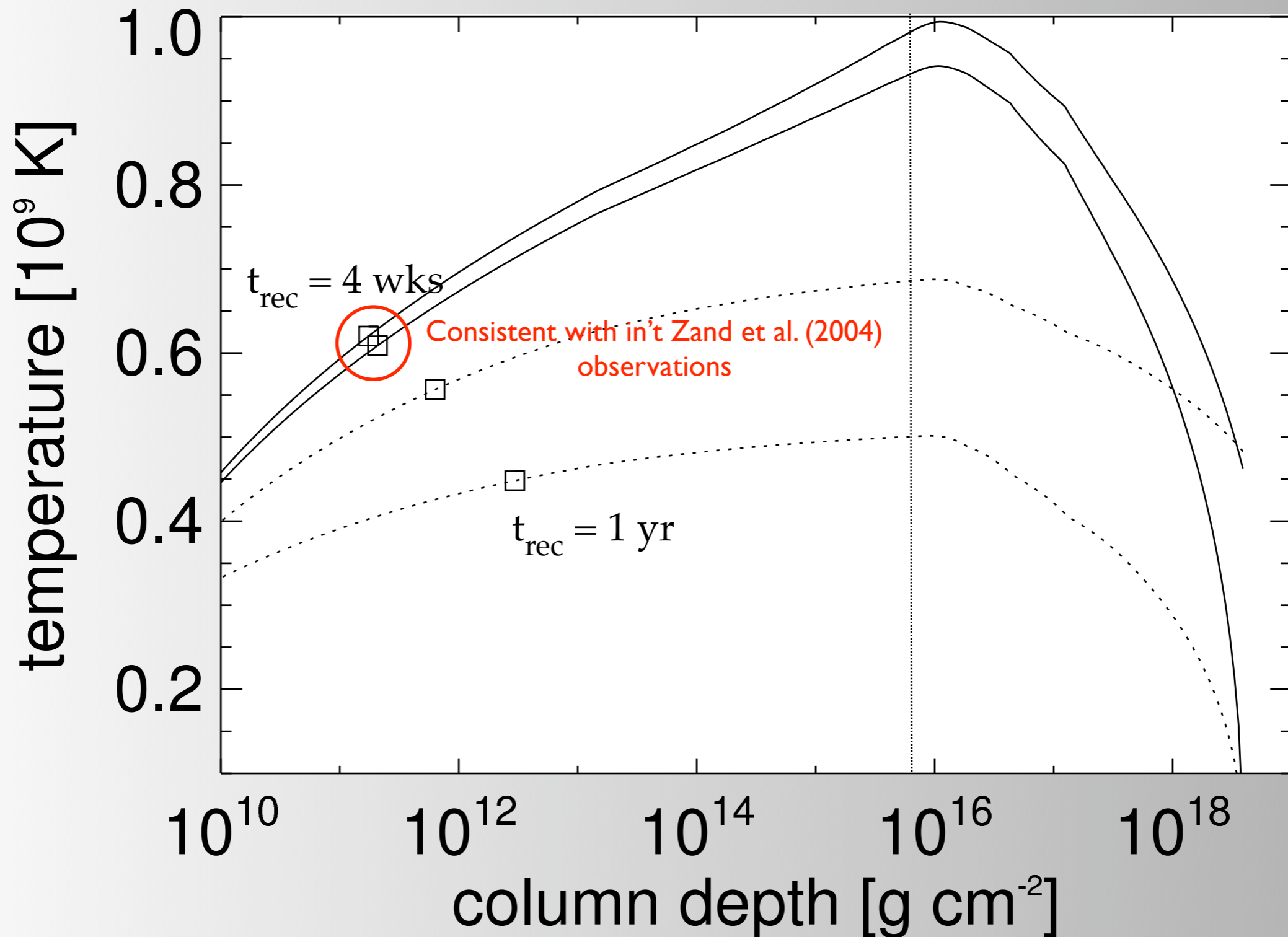
- Steeper ∇T if ocean is *not* pure C
- Matched recurrence times and energetics
- Does not account for thermal balance in the crust



Ignition columns and recurrence times



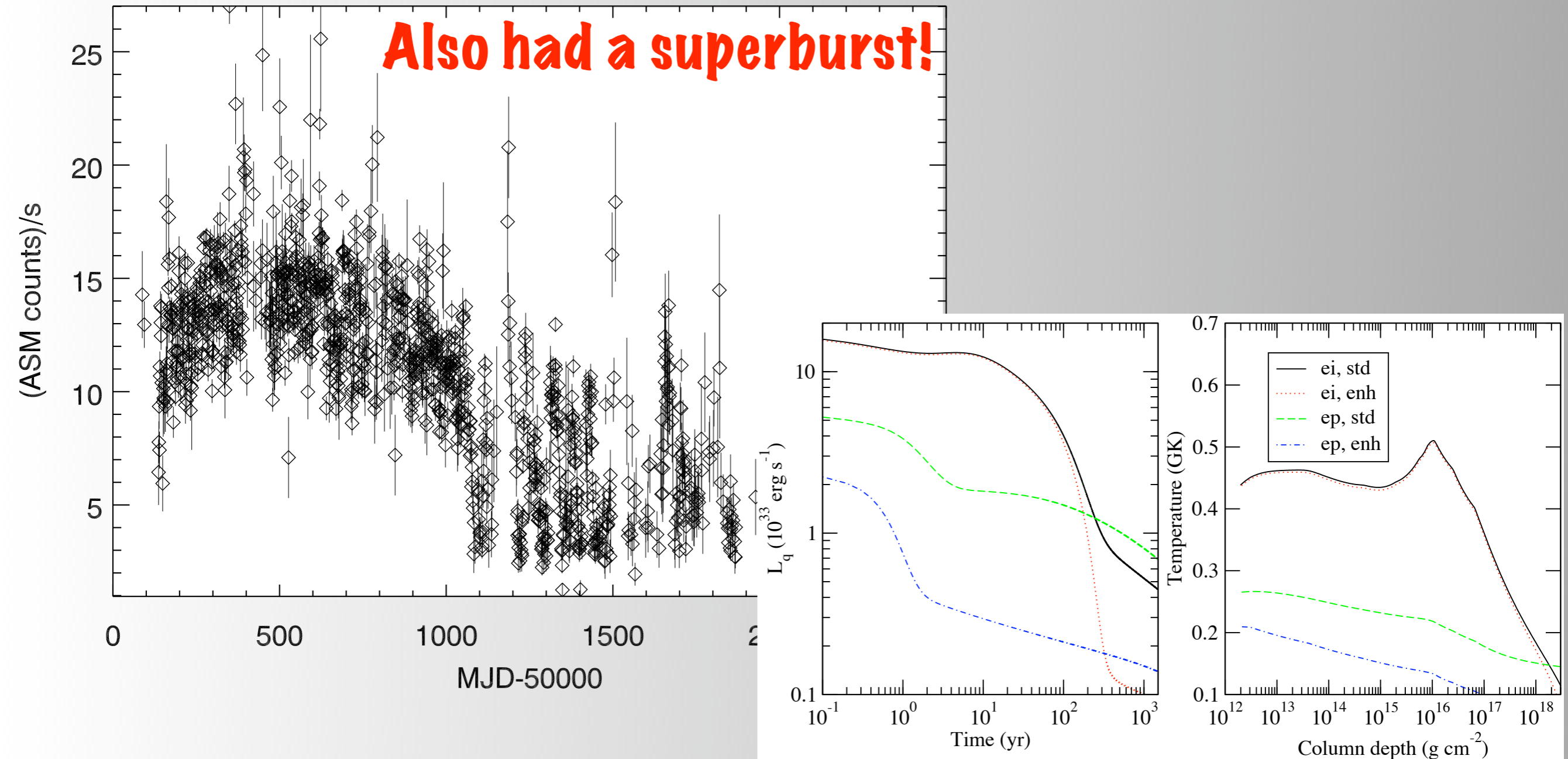
Recent discovery (in't Zand et al. 2004) of
superbursts at large $dM/dt = 10^{18} \text{ g s}^{-1}$



Brown 2004

Cooling after a long outburst

Rutledge et al. 2002; also Wijnands 2001



Rutledge et al. 2002
Ouellette & Brown, in preparation

Summary

- accreting neutron stars offer several probes into the nature of dense matter
 - soft X-ray transients
 - spectra reasonably well-understood: fit R
 - measurements of L_q over time
 - superbursts
 - recurrence time energetics sensitive to thermal state of deep crust and core